REMARKS

Reconsideration and allowance of the subject application are respectfully solicited.

Claims 1, 3 through 15, 29, 31 through 33, 35 through 37, and 39 through 45 are pending, with Claims 1, 15, 33, 35, 41, 42, and 44 being independent. Claims 30, 34, and 38 have been cancelled.

Claims 1, 15, 33, 35, 41, 42, and 44 have been amended. Applicant submits that no new matter has been added.

Claims 1, 3 through 11, 15, and 29 through 45 were rejected under 35 U.S.C. § 103 over commonly-assigned U.S. Patent No. 6,225,637 B1 (Terashima, et al.) in view of newly-cited U.S. Patent No. 4,389,571 (Crewe). Claims 12 and 13 were rejected under 35 U.S.C. § 103 over Terashima, et al. and Crewe in view of U.S. Patent No. 4,954,717 (Sakamoto, et al.). Claim 14 was rejected under 35 U.S.C. § 103 over Terashima, et al., Crewe, and Sakamoto, et al., and further in view of U.S. Patent No. 4,469,949 (Mori, et al.). These rejections are respectfully traversed.

Applicant appreciates the courtesies extended by Examiner Vanore in granting and conducting a personal interview with Applicant's representative on March 17, 2005. During the interview, Applicant's representative provided copies of two papers entitled "Seidel Aberrations" and "The Five Seidel Aberrations." Copies of those papers are attached. Those documents were obtained from the Internet to provide additional explanation regarding the Seidel aberrations.

As explained during the interview, there are five aberrations collectively known as the Seidel aberrations, and all five of these are third-order aberrations. Included among those

third-order aberrations is image distortion. However, image distortion can also occur as a fifth-order aberration. The present application discloses, *inter alia*, an invention in which third-order image distortion and fifth-order image distortion can cancel each other. This is disclosed, for example, at least in the discussion regarding Fig. 6 at page 24, lines 11-20 of the specification.

Applicant's representative proposed a claim amendment during the interview to clarify the distinctions between the claimed invention and the cited art. In particular, Applicant's representative proposed that the language "so that third-order image distortion and fifth-order image distortion substantially cancel each other" be inserted at the end of Claim 1, and that a similar amendment be made to each of the other independent claims. As argued during the interview, none of the cited art discloses or suggests controlling magnetic lenses in such a way that third-order image distortion and fifth-order image distortion substantially cancel each other.

The Examiner agreed during the interview that the cited art does not disclose or suggest this feature. Pending approval of his supervisor, the Examiner indicated that the proposed amendment would overcome the outstanding rejections, although an updated search would be required before the application can be allowed.

In view of the foregoing, Applicant submits that the cited art fails to disclose or suggest the above-mentioned feature of the present invention recited in each of the independent claims, and therefore Applicant submits that those claims are patentable. The dependent claims are also patentable for at least the reasons discussed with respect to the independent claims, as well as for the additional features they recite.

Applicant submits that this application is in condition for allowance. Favorable reconsideration, entry of the above amendments, withdrawal of the outstanding rejections, and an early Notice of Allowance are respectfully requested.

Applicant's undersigned attorney may be reached in our Washington, D.C. office by telephone at (202) 530-1010. All correspondence should continue to be directed to our address given below.

Respectfully submitted,

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The Five Seidel Aberrations

The five basic types of aberration which are due to the geometry of lenses or mirrors, and which are applicable to systems dealing with monochromatic light, are known as *Seidel* aberrations, from an 1857 paper by Ludwig von Seidel. These are the aberrations that become evident in *third-order optics*, also known as Seidel optics.

As we know,

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \frac{x^9}{9!} - \frac{x^{11}}{11!} + \frac{x^{13}}{13!} - \ldots$$

and

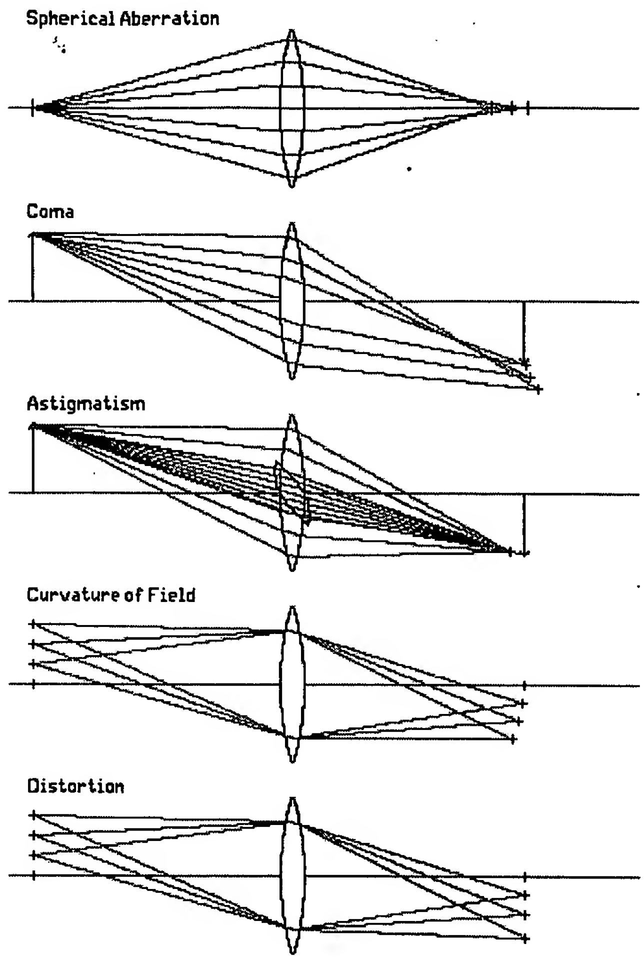
$$\cos(x) = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \frac{x^8}{8!} - \frac{x^{10}}{10!} + \frac{x^{12}}{12!} - \ldots$$

When we neglect the later terms in the series, so that we behave as if sin(x) = x, and cos(x) = 1, we obtain first-order optics, in which all lenses are perfect. When we include the x squared and x cubed terms, then we have proceeded to third-order optics, in which the aberrations resulting from the nature of real lenses, exclusive of chromatic aberration, become evident.

The five Seidel aberrations are:

- **Spherical Aberration**: this is the aberration affecting rays from a point on the optical axis; because rays from this point going out in different directions pass through different parts of the lens, then, if the lens is spherical, or otherwise not the exact shape needed to bring them all to a focus, then these rays will not all be focused at the same point on the other side of the lens.
- **Coma**: this aberration affects rays from points off the optical axis. If spherical aberration is eliminated, different parts of the lens bring rays from the axis to the same focus. But the place where the image of an off-axis point is formed may still change when different parts of the lens are considered.
- **Astigmatism**: this is another aberration affecting rays from a point off the optical axis. These rays, as they head through the lens to the point in the image where they will be focused, pass through a lens that is, from their perspective, tilted. Even if neither spherical aberration nor coma prevents them from coming to a sharp focus, if we consider the rays of light that are in the plane of the tilt, and the rays of light that are in the plane perpendicular to that, these rays pass through a part of the lens with a different profile. So they may not be focused at the same distance from the lens, even if they do come to a focus in each case.
- **Curvature of Field**: even when light from every point in the object is brought to a sharp focus, the points at which they are brought into focus might lie on a curved surface instead of a flat plane.
- **Distortion**: even when all the previous aberrations have been corrected, the light from points in the object might be brought together on the image plane at the wrong distance from the optical axis, instead of being linearly proportional to the distance from the optical axis in the object. If distance increases faster than in the object, one has *pincushion* distortion, if more slowly, *barrel* distortion.

The following diagram attempts to illustrate these aberrations:



Since we know the exact laws which govern the operation of lenses and mirrors, it is possible to determine the exact course of light through any optical system by means of *ray tracing*. At one time, this was a very laborious procedure, but now it can be carried out automatically by computers, and, as well, computers are no longer expensive.

However, simply choosing optical designs at random, and then finding out whether or not they work is not likely to get one anywhere fast. Instead, one needs a sense of what kind lenses will work together in a design to compensate for each other's aberrations. Knowledge of a large number of existing optical designs is one way to address this difficulty. Third-order optics, because it breaks down the aberrations of lenses into five quantities that can be manipulated arithmetically, also plays a considerable role in finding a starting point for a new optical design.

The two kinds of chromatic aberration bring the total to seven. There are also higher-order aberrations. Sometimes, it is so important to combat chromatic aberration, that one tries to suppress the *secondary spectrum* left over from an achromatic lens that brings two wavelengths together, and using three kinds of glass, bring three wavelengths together to create an *apochromat*. Also, given that there is chromatic aberration, a lens system with two kinds of glass, designed to correct the five Seidel aberrations for one wavelength of light will, even if built out of closely spaced achromats, still have these aberrations for other wavelengths; thus, the chromatic variation in the aberrations is another higher-order consideration. As well, going to higher-order terms in the expansion of the sine and cosine functions leads to an additional set of nine aberrations at the next step.

Usually, except for designing an apochromat, it isn't helpful to think in terms of the higher-order aberrations directly; their effects were minimized through actual ray-tracing even in the days when the

calculations for it were done by hand.

To get rid of aberration in optical design, understanding it in terms of the five Seidel aberrations is helpful. We need two things to benefit from this help. We need a simple formula for the aberrations a spherical refracting surface will cause. The formula can be approximate, as long as it gives us the right answer for when the aberrations become small. And we need a way to combine the aberrations from multiple lenses.

It turns out this is possible. One reason for that is that multiplication can sometimes be approximated by addition. So if a and b are both much smaller than one, (1+a) times (1+b), which is (1+a+b+ab), is approximately 1+a+b. So, if a and b are thought of as deviations from perfection (multiplying by 1) the deviations can be treated as simply adding even when multiplication is the correct rule. Another is that distorted images do pass through successive lenses in a simple way. This is particularly obvious in the case of the aberration of distortion: an image with only that aberration is still an image in focus on a flat plane, so it would be magnified the same way the original object would be by successive lenses. In the case of other aberrations, one optical law is the key to following them through an optical system.

If a lens magnifies an object N times, (small) **front-to-back distances in the object are magnified N squared times.**

This gives us the rule by which we can scale the aberration of any lens in an optical system, to determine its contribution to the aberration of the system as a whole.

[Up] [Previous]

Seidel Aberrations

The wavefront emerging from a real lens is complex

- Errors in the design
- Fabrication
- Assembly of the lens.

Nevertheless, well made and carefully assembled lenses possess certain inherent aberrations.

- It is conventional to refer to certain aberrations, regardless of whether caused by an inherent defect of the lens or a combination of manufacturing errors.

To describe the primary monochromatic aberrations of ***rotationally symmetrical optical systems*** we specify the shape of the wavefront emerging from the exit pupil.

- For each object point, there will be a quasi-spherical wavefront converging toward the paraxial image point.
  - A particular image point is specified by giving the paraxial image coordinates (x_0, y_0).
  - The wavefront can be expanded as a power series in the four variables (x, y) (exit pupil coordinates) and (x_0, y_0) (image coordinates).

By rotational symmetry, W is invariant on rigid rotation of x_0, y_0 and x, y axes about the z-axis.

- Select the coordinate system such that the image point lies in the x/z plane so $y_0 = 0$.
  - W can be expanded as

$$\begin{aligned} W(x, y, x_0) &= W(x^2 + y^2, xx_0, x_0^2) \\ &= a_1(x^2 + y^2) + a_2 xx_0 + a_3 x_0^2 + b_1(x^2 + y^2)^2 \\ &\quad + b_2 xx_0(x^2 + y^2) + b_3 x^2 x_0^2 + b_4 x_0^2(x^2 + y^2) \\ &\quad + b_5 xx_0^3 + b_6 x_0^4 + \ldots , \end{aligned}$$

... represents neglected higher order terms

  - The first term is defocus, a longitudinal shift of the center of the reference sphere.
  - The second term is a transverse shift of the center of the reference sphere, or tilt.
  - The third term gives rise to a constant phase shift across the exit pupil
    - No effect on the image.
    - For monochromatic light, these three terms normally have zero coefficients.
    - However, they are nonzero for white light, and describe chromatic aberrations.

- The terms with coefficients b_1 to b_6 are of fourth degree in x, y, and x_0,
  - Third degree when expressed as transverse ray aberrations.
  - Commonly known as ***third-order aberrations***.
  - Succeeding groups of higher order terms are ***fifth- and seventh-order aberrations***.
- The first five third-order aberrations are named for L. Seidel, who in 1856 gave explicit formulae for calculating them.

Polar exit pupil coordinates are used for the Seidel aberrations.

$$x = \rho\cos\theta \quad \text{and} \quad y = \rho\sin\theta.$$

The radial coordinate, ρ, is usually normalized so that it equals 1 at the edge of the exit pupil. The field coordinate x_0 is also usually normalized to 1 at the maximum field point. Normalized coordinates will be used hereafter.

In polar coordinates (ρ, θ), the wavefront expansion of can be written in terms of wavefront aberration coefficients W_{jmn} :

$$\begin{aligned} W(x_0,\rho,\theta) &= \sum_{j,m,n} W_{klm}\, x_0^k \rho l \cos^m\theta \\ &= W_{200}x_0^2 + W_{111}x_0\rho\cos\theta + W_{020}\rho^2 \\ &\quad + W_{040}\rho^4 + W_{131}x_0\rho^3\cos\theta + W_{222}x_0^2\rho^2\cos^2\theta \\ &\quad + W_{220}x_0^2\rho^2 + W_{311}x_0^3\rho\cos\theta \end{aligned}$$

with $k = 2j + m$ and $l = 2n + m$.

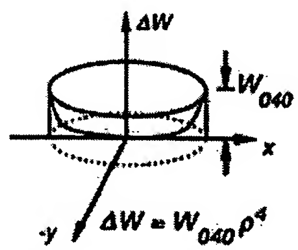
In Seidel aberration coefficients, S_i

$$\begin{aligned} W(x_0,\rho,\theta) &= \frac{1}{8}S_I\rho^4 + \frac{1}{2}S_{II}x_0\rho^3\cos\theta + \frac{1}{2}S_{III}x_0^2\rho^2\cos^2\theta \\ &\quad + \frac{1}{4}(S_{III} + S_{IV})x_0^2\rho^2 + \frac{1}{2}S_V\, x_0^3\rho\cos\theta. \end{aligned}$$

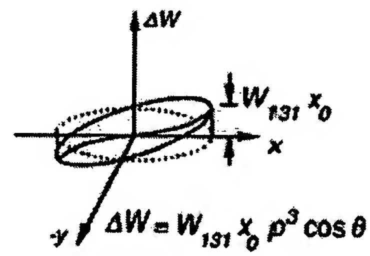
Wavefront Aberration Coefficient	Seidel Aberration Coefficient	Form	Name
W_{200}		x_0^2	Piston
W_{111}		$x_0\rho\cos\theta$	Tilt
W_{020}		ρ^2	Focus
W_{040}	$S_I/8$	ρ^4	Spherical

W_{131}	$S_{II}/2$	$x_0\rho^3\cos\theta$	Coma
W_{222}	$S_{III}/2$	$x_0^2\rho^2\cos^2\theta$	Astigmatism
W_{220}	$(S_{III}+S_{IV})/4$	$x_0^2\rho^2$	Field curvature
W_{311}	$S_V/2$	$x_0^3\rho\cos\theta$	Distortion

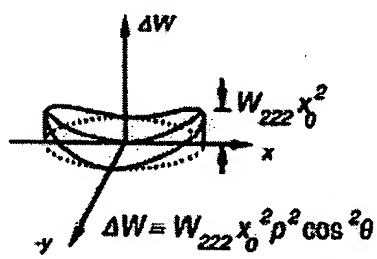
Piston, tilt, and focus are first-order properties of the wavefront and are not Seidel aberrations.



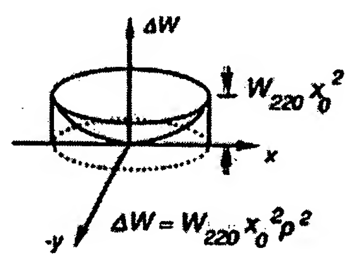
Spherical Aberration



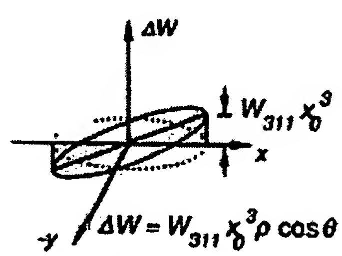
Coma



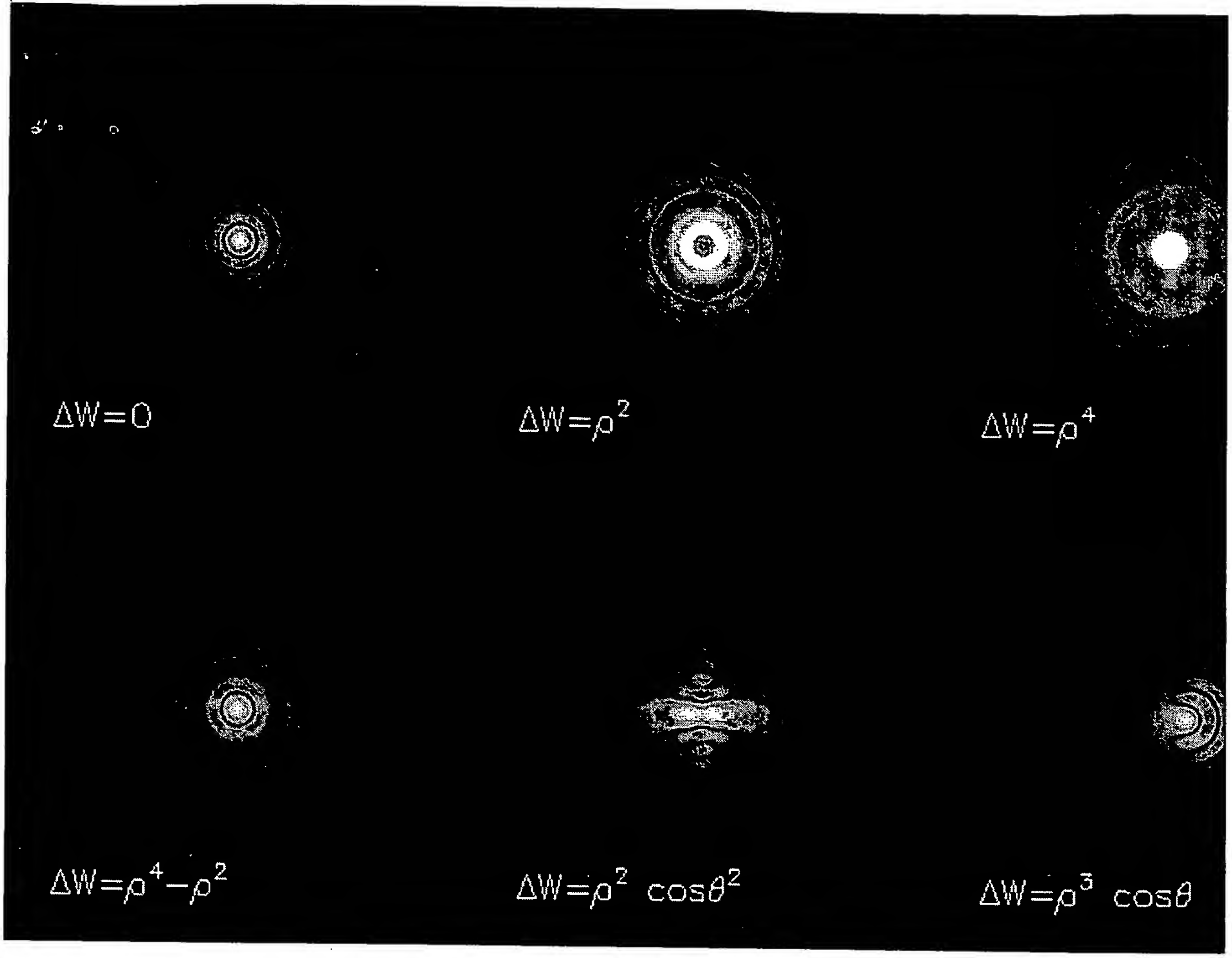
Astigmatism



Field Curvature



Distortion


ΔW=0
ΔW=ρ²
ΔW=ρ⁴
ΔW=ρ⁴−ρ²
ΔW=ρ² cosθ²
ΔW=ρ³ cosθ
